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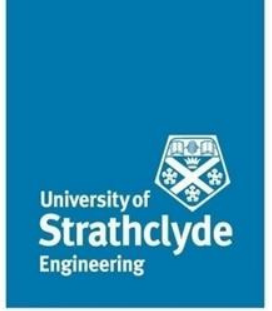
**Murray, D. and Zhao, B. and Elafoudi, G. and Liao, J. and Stankovic, L. and Stankovic, V. (2014) Combined Network Coding and Paillier homomorphic encryption for ensuring consumer data privacy in smart grid networks. In: Algebra, Codes and Networks 2014, 2014-06-16 - 2014-06-20. ,**

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# Combined Network Coding and Paillier Homomorphic Encryption for ensuring Consumer Data Privacy in Smart Grid Networks



Presented by David Murray, PhD candidate on behalf of the team:

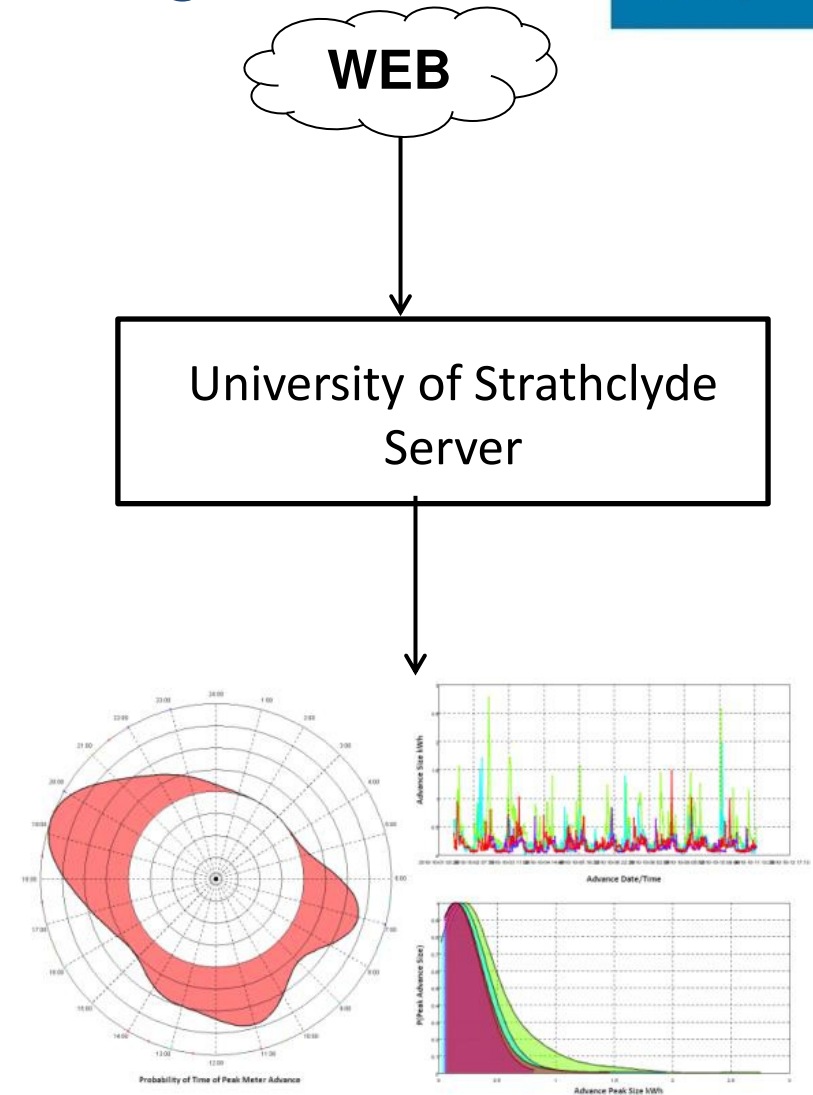
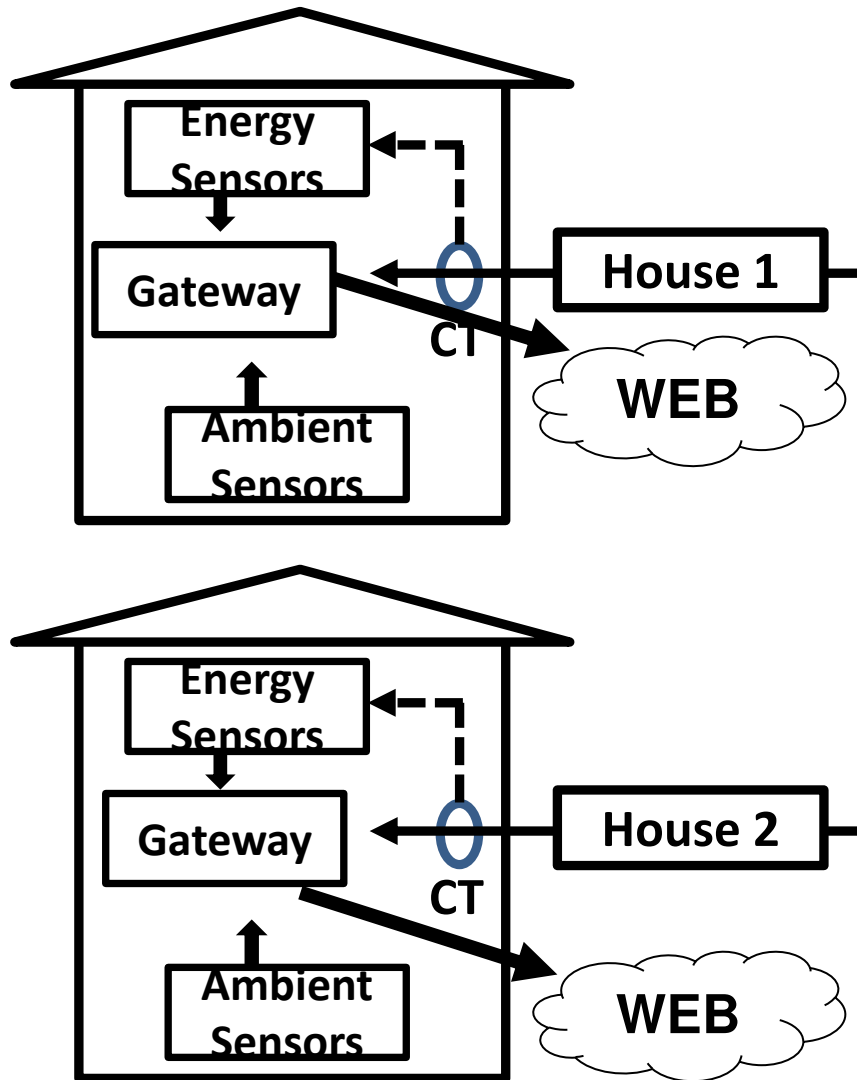
D. Murray, B. Zhao, G. Elafoudi, J. Liao, L. Stankovic, V. Stankovic  
Centre for Intelligent and Dynamic Communications  
University of Strathclyde, Glasgow, UK

# Monitoring domestic energy usage within the smart grid

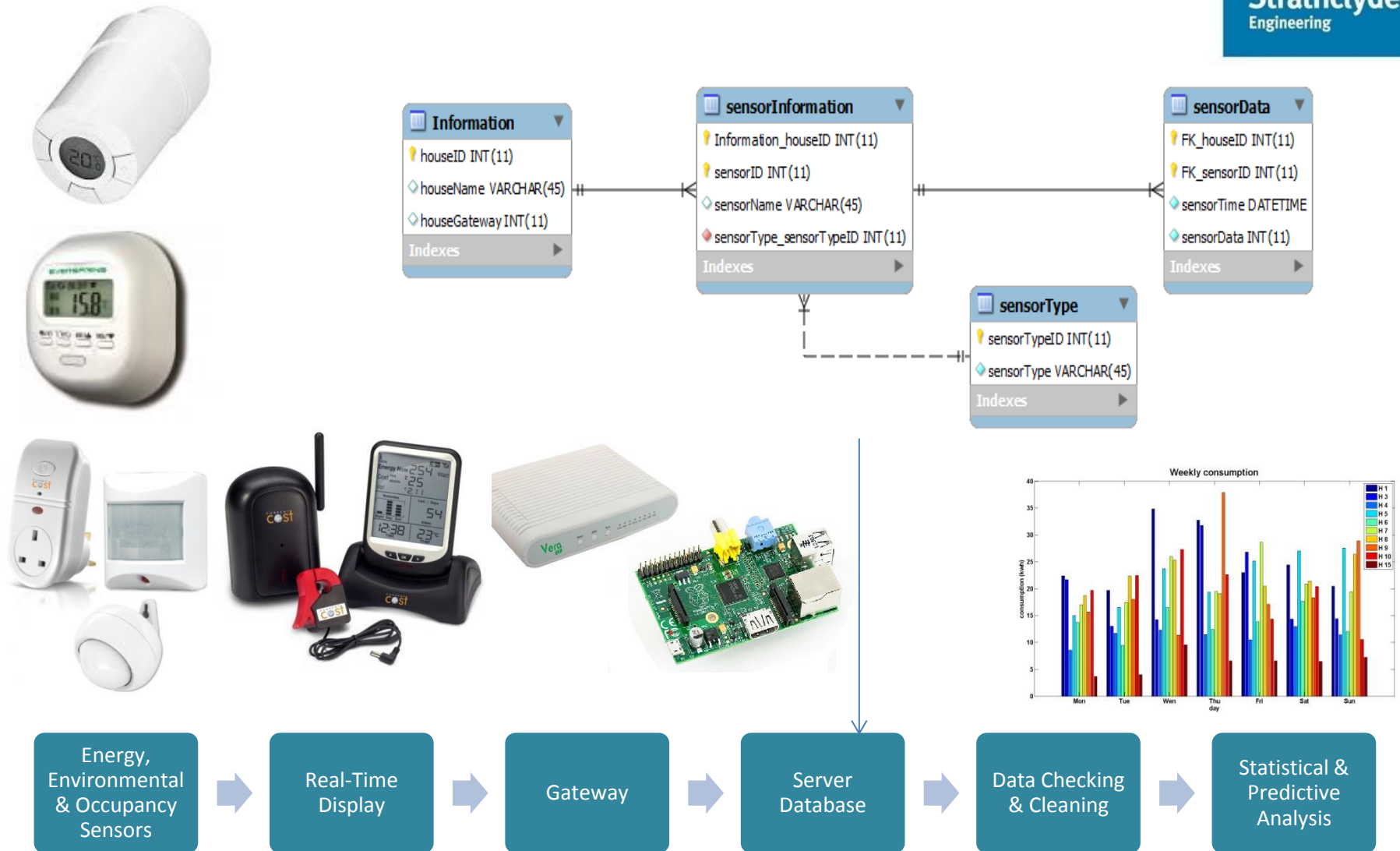
- How will smart meters be used?
  - Automatic and accurate billing, improve energy usage
  - Enhance energy distribution and efficiency
- How can signal information processing/data analytics turn smart meter data into 'useful' information?
  - Inform and enhance current energy information
  - Provide itemised billing down to individual appliances and activities
  - Provide advice on retrofit advice
- How much and what kind of data do we need for effective data analytics?
  - Electricity, temperature, light, humidity, occupancy
  - Data collection 15mins, 1min, 30 sec, 1sec...
- Can we draw better conclusions from individual/household detailed energy consumption?

- How is data collected, where does it go?
- How do we ensure privacy of data and detect tampering?

# How we implemented it at Strathclyde to gather smart meter readings



# From data acquisition to analytics



# Analytics to provide intuitive feedback

- We developed a scalable database that effectively manages incoming smart meter data, and provides an easy-to-query design
- Designing and developing robust and low-complexity non-intrusive load monitoring disaggregation algorithms for low sampling rate load data ( $< 1$  Hz)
- Appliance characterisation and modelling to provide appliance upgrade recommendations

# Data acquisition, management and repository

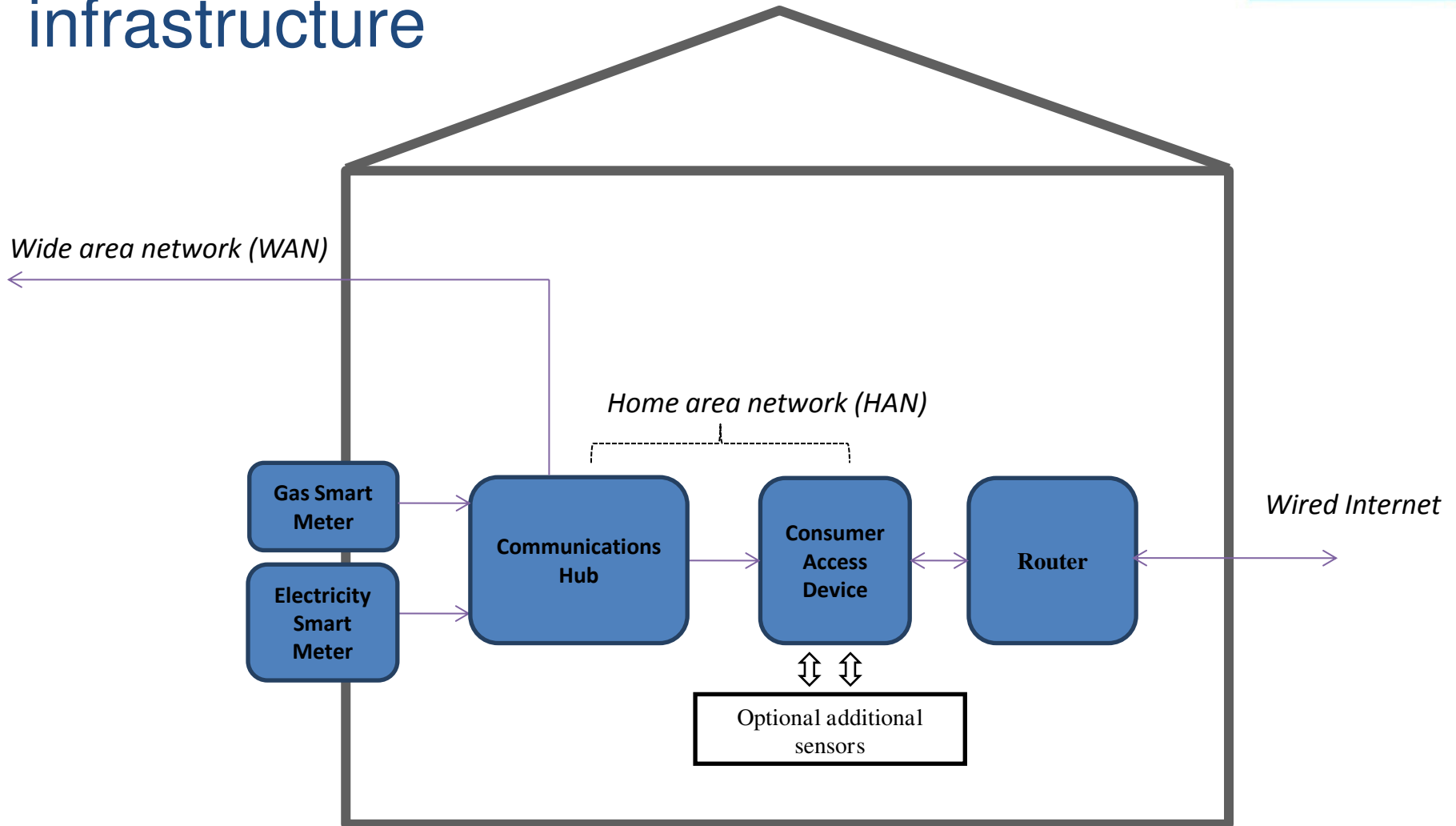
- An automated platform for remote data collection and real-time monitoring
  - Including remote and non-broadband customers
  - Keeping communications between home and server to a bare minimum, without compromising on data quality
  
- Scalable repository of energy and environmental measurements
  - Data checking
  - Easy to add/remove sensors and houses
  - Query for correlations amongst sensor readings in the database
  - Query for correlations across houses (e.g., compare refrigerator consumption across selected houses)
  - Collecting/processing data in real time from a large number of houses (currently 40 houses)

# Power Disaggregation

- Non-intrusive appliance load monitoring (NALM): Algorithmic solutions to disaggregate overall household's power readings to individual appliances
- Find the consumption of individual appliances without using separate individual appliances power meters (IAMs)
- Activity modelling allows for more relative feedback that people can understand and adjust habits
  - Improve: You used X amount of power yesterday on the kettle
  - If you didn't over fill the kettle you could save.
- Very active research topic
  - Currently, only few commercial solutions that operate well, work only at extremely high sampling rates ~kHz



# Smart Meter readings – UK Dept of Energy and Climate Change infrastructure



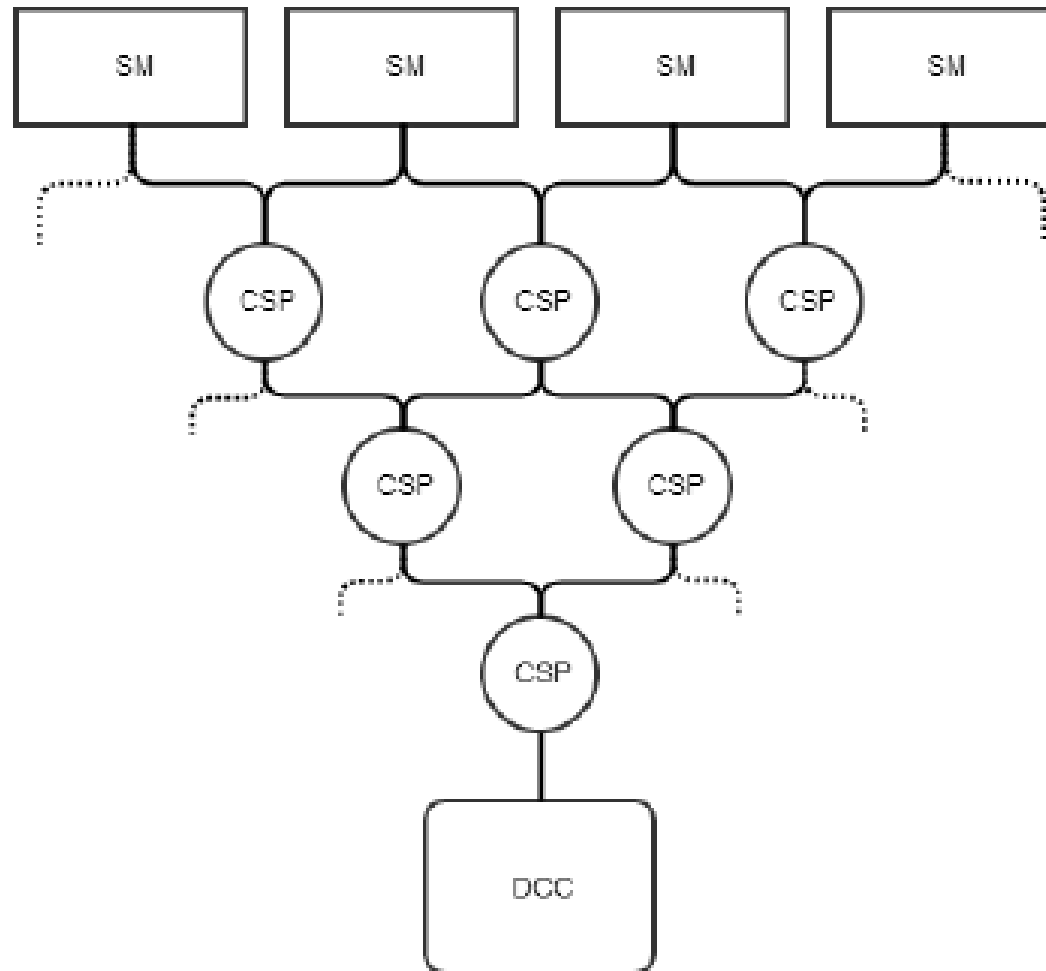
Block diagram from REFIT project team

# Smart grid communications architecture



- Smart metering (SM) system located in houses comprises of a hub and sensor network
  - HAN based on 2.4GHz and 433MHz
- From the houses, data transmitted to Communications Service Provider (CSP) via wireless NAN
  - Communication range 0.25miles
  - At least two CSPs in the range of each house
  - CSPs – routers that forward packets possibly multi-hops
- Data Communication Company (DCC) receives packets from CSP and performs processing

# Smart grid communications architecture



# Problem statement

- Lots of sensitive personal household data being gathered within the HAN and transmitted via WAN/NAN
- Data contains billing information and energy consumption from which domestic routines can be inferred, inc. when the household is away on holiday...

# Security in the smart grid

- Smart grid prone to cyber attacks and tampering due to sensitivity of information in the network
- Key concern is against tampering, eavesdropping and traffic analysis
- Types of attacks expected:
  - Entropy Attacks
  - Packet Erasures
  - Packet Modification / Corruption
  - Eavesdropping / Analysis

# Proposed Solution

- Pairing network coding (NC) with Paillier homomorphic encryption (PHE)
- Due to its homomorphic additive and multiplicative properties, PHE simplifies computation of cipher texts and incorporation of linear NC
- *Intermediate nodes can still perform NC in the conventional manner without needing access to the systems private key*

# Random Linear Network Coding (RLNC)

$$\mathbf{X} = \mathbf{G} * \mathbf{M}$$

$$x_k = \sum_{i=1}^S g_{ik} m_i$$

$$\mathbf{G} = \begin{bmatrix} g_{11} & g_{12} & \dots & \dots & g_{1S} \\ g_{21} & g_{22} & \dots & \dots & g_{2S} \\ \dots & \dots & \dots & \dots & \dots \\ \dots & \dots & \dots & \dots & \dots \\ g_{N1} & g_{N2} & \dots & \dots & g_{NS} \end{bmatrix}$$

$$\mathbf{M} = \begin{bmatrix} m_1 \\ m_2 \\ \dots \\ m_S \end{bmatrix}$$

- $k$ -th NC symbol/packet
- $m_i$  –  $i$ -th source message
- $g_{ik}$  random local encoded coefficient

## Benefits compared against traditional routing

- Throughput
- Efficiency
- Scalability
- Resilience to attacks and eavesdropping

## Issues

- Larger transmission overhead
- Linear dependency of coefficient vectors

# Paillier Homomorphic Encryption (PHE)

$p, q$  are two  $k$ -bit primes where  $k$  is the security parameter, are random and independent such that:

$$\gcd(pq, (p-1)(q-1)) = 1$$

$$n = pq$$

$$\lambda = \text{lcm}((p-1)(q-1))$$

Choose random integer  $g$  where:

$$g \in \mathbb{Z}_{n^2}^*$$

Check modular multiplicative inverse:

$$\mu = \left( L(g^\lambda \bmod n^2) \right)^{-1} \bmod n \quad \text{where} \quad L(\mu) = \frac{\mu - 1}{n}$$

Public Key :  $(n, g)$

Private Key :  $(\lambda, \mu)$



# PHE: Encryption and Decryption

## Encryption:

For a message  $m \in \mathbb{Z}_n$   
Select random  $r \in \mathbb{Z}_n^*$   
Calculate ciphertext using public key:  
 $E(m) = c = g^m r^n \bmod n^2$

## Decryption:

Given received ciphertext  $c < n^2$ ,  
recover the message using private key:  
 $m = D(c) = L(c^\lambda \bmod n^2) \mu \bmod n^2$

## *Homomorphic Properties*

$$E(m) = (g^m r^n) \bmod n^2$$

$$E(m_1)E(m_2) = g^{m_1+m_2} (r_1 r_2)^n \bmod n^2 = E(m_1 + m_2)$$

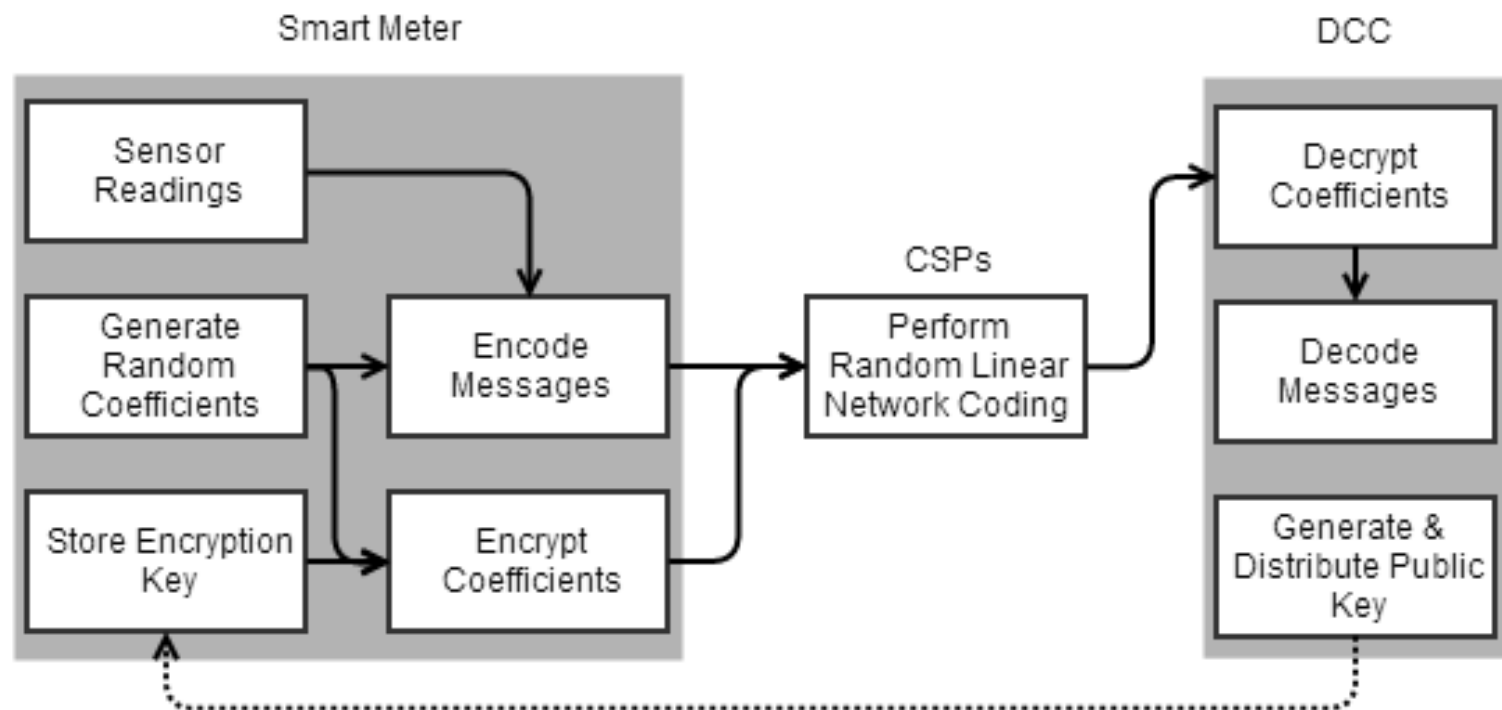
$$D(E(m_1)^k \bmod n^2) = km_1 \bmod n$$

# Threat model

We consider the threat posed by an attacker with the following characteristics:

- The attacker can eavesdrop all network links
- Has knowledge of scheme used
- Is computationally bounded
- Can inject or erase packets in the network

# Proposed scheme



# Proposed scheme – Combined RLNC and PHE encryption

- Each house SM system performs NC on its HAN dataset
- The local encoding vectors used are then encrypted using the public key

$$c_i(e) = E_{ek}(g_i(e)), (1 \leq i \leq h)$$

$$c(e) = [c_1(e), c_e(e), \dots, c_h(e)]$$

- CSP performs conventional NC on all incoming encoded and encrypted packets from the houses

$$g(e) = \sum_{i=1}^h \beta_i(e) g(e'_i)$$

$$E_{ek}(g(e)) = E_{ek}\left(\sum_{i=1}^h \beta_i(e) g(e'_i)\right)$$

$$= \prod_{i=1}^h E_{ek}(\beta_i(e) g(e'_i))$$

$$= \prod_{i=1}^h E_{ek}^{\beta_i(e)}(g(e'_i))$$

$$\mathbf{M}_1 = [\mathbf{m}_1^1 \mathbf{m}_2^1]$$

$$\mathbf{X}_1 = \mathbf{G}_1 \mathbf{M}_1$$

$$E(g_{11}^1), E(g_{12}^1) \quad \mathbf{X}_{11}$$

$$E(g_{21}^1), E(g_{22}^1) \quad \mathbf{X}_{12}$$

House1  $\vdots$

$$\mathbf{M}_2 = [\mathbf{m}_1^2 \mathbf{m}_2^2]$$

$$\mathbf{X}_2 = \mathbf{G}_2 \mathbf{M}_2$$

$$E(g_{11}^2), E(g_{12}^2) \quad \mathbf{X}_{21}$$

$$E(g_{21}^2), E(g_{22}^2) \quad \mathbf{X}_{22}$$

$\vdots$  House2

$$\quad \mathbf{X}_{11}$$

$$\quad \mathbf{X}_{21}$$

$\vdots$

$\mathbf{X}$

CSP

$$\longrightarrow \mathbf{X}^{\text{CSP}} = \mathbf{G}^{\text{CSP}} \mathbf{X}$$

$$(E(g_{11}^1))^{g_{11}^{\text{CSP}}}, (E(g_{12}^1))^{g_{12}^{\text{CSP}}} \quad \mathbf{X}_{11}^{\text{CSP}}$$

# Proposed Scheme – Decoding & Decryption at Sink

- DCC/sink will first decrypt NC coefficients
- Resulting global encoding vectors are used for RLNC decoding in the conventional way, e.g., using Gaussian elimination
- Note that all houses have knowledge of the public key and only the DCC has knowledge of the private key for decryption
- At the sink decryption can be carried out once a sufficient number of packets from the same generation has been received

- $$\begin{bmatrix} x_1 \\ \vdots \\ x_h \end{bmatrix} = G^{-1} \begin{bmatrix} x^{csp}(e_1) \\ \vdots \\ x^{csp}(e_h) \end{bmatrix}$$

$$(E(g_{11}^1))^{g_{11}^{CSP1}}, (E(g_{12}^1))^{g_{12}^{CSP1}}$$

$$X_{11}^{CSP1}$$

$$(E(g_{11}^1))^{g_{11}^{CSP2}}, (E(g_{12}^1))^{g_{12}^{CSP2}}$$

$$X_{11}^{CSP2}$$



Decrypt encoding coefficients

$$D((E(g_{11}^1))^{g_{11}^{CSP1}}) = g_{11}^{CSP1} g_{11}^1$$



Gaussian Elimination for NC decoding

$\overline{M}$  Recovered message

*DCC*

# Analysis

- Is efficient and does not incur a significantly high overhead
- Features privacy against packet analysis
- Encryption prevents against earliest decoding by packet analysis
- Each message is of the same size helping prevent size correlation and buffering reduces effect of time order correlation attacks
- Inefficient against Pollution and Entropy attacks

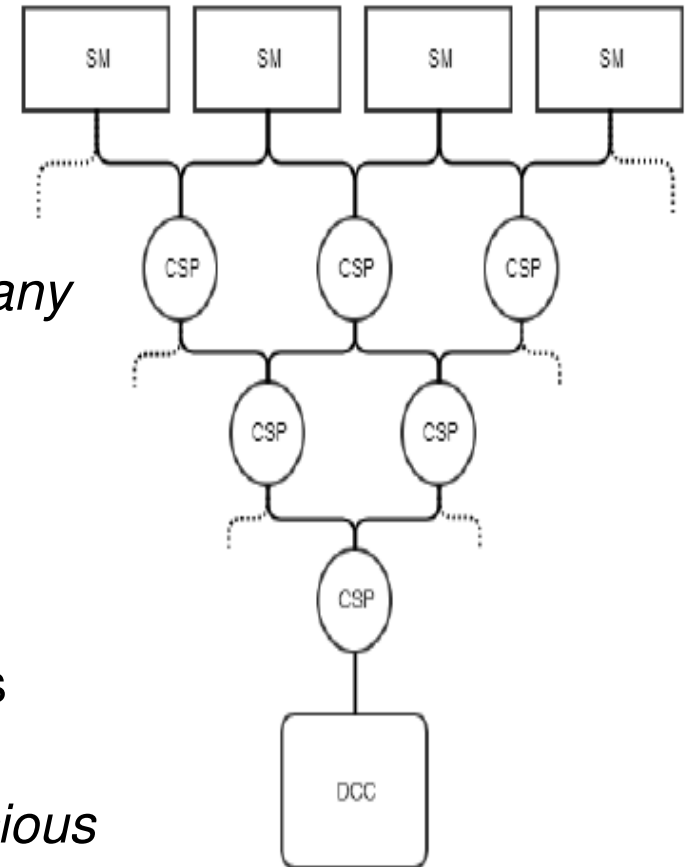


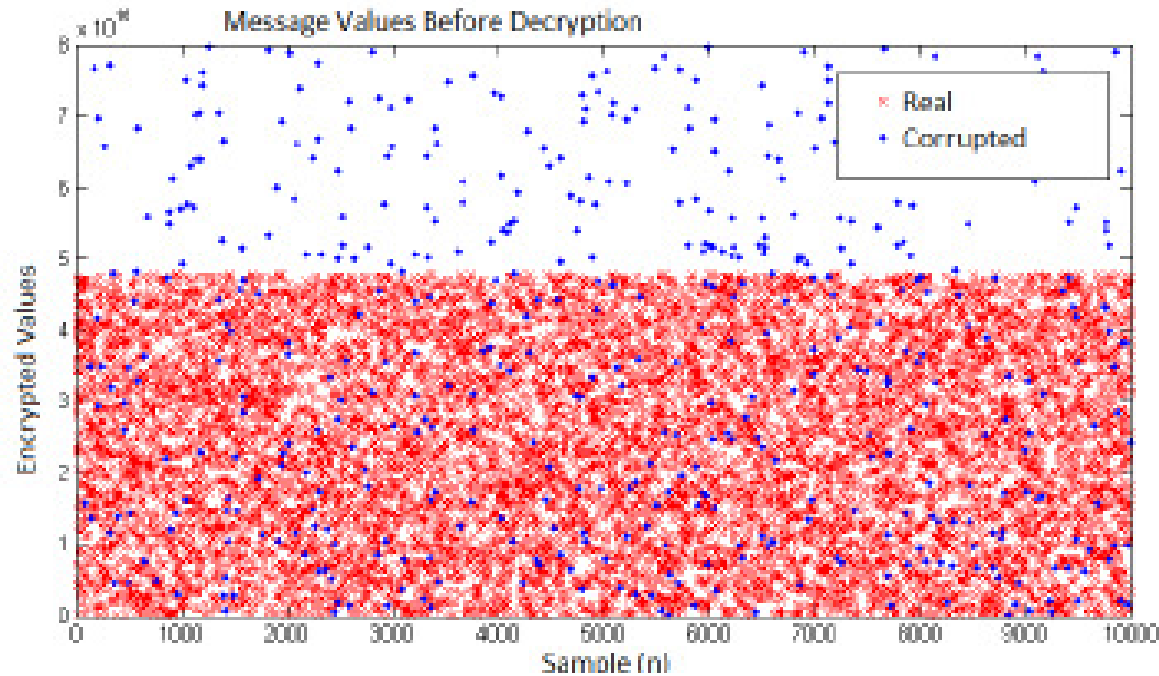
# Resilience to packet drops

- CSPs dropping incoming packets
- RLNC provides erasure protection, and additional PHE does not affect erasure protection of RLNC
- Lemma1: *If only one CSP is dropping all packets it receives, then all messages from any house can be recovered at the DCC*

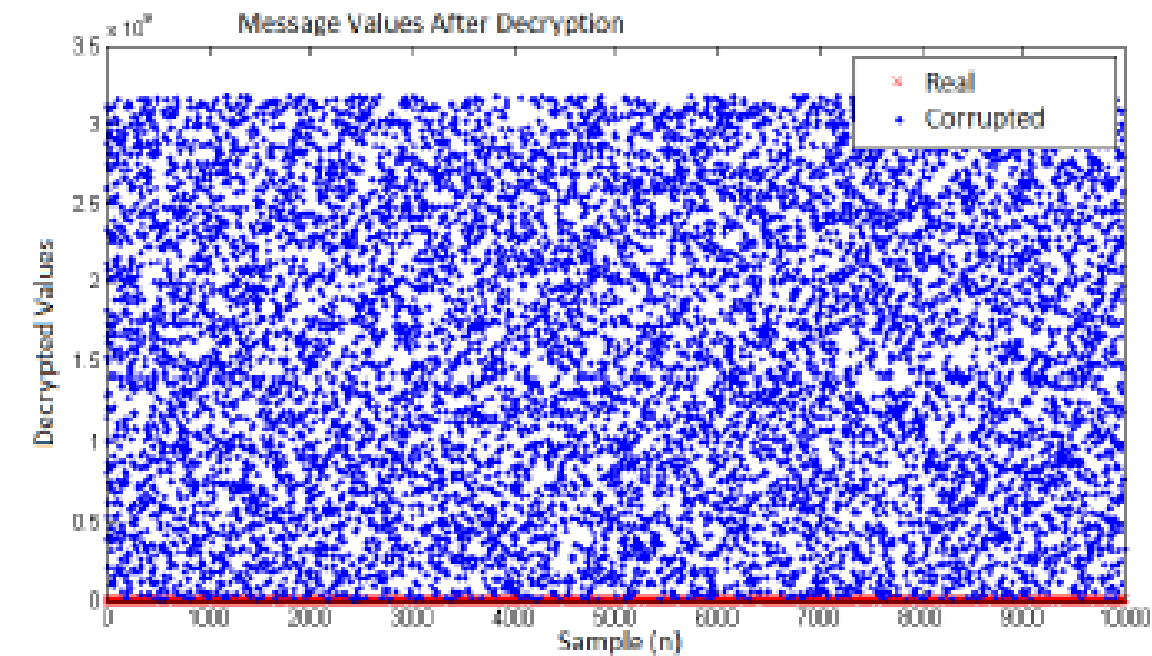
## Pollution and entropy attacks

- Attacker injects dummy packets
- CSP can generate malicious content that is mixed with incoming packets
- Lemma2: *If only one CSP is injecting malicious content and mixing it with incoming packets, then all messages from any house can be recovered at the DCC*



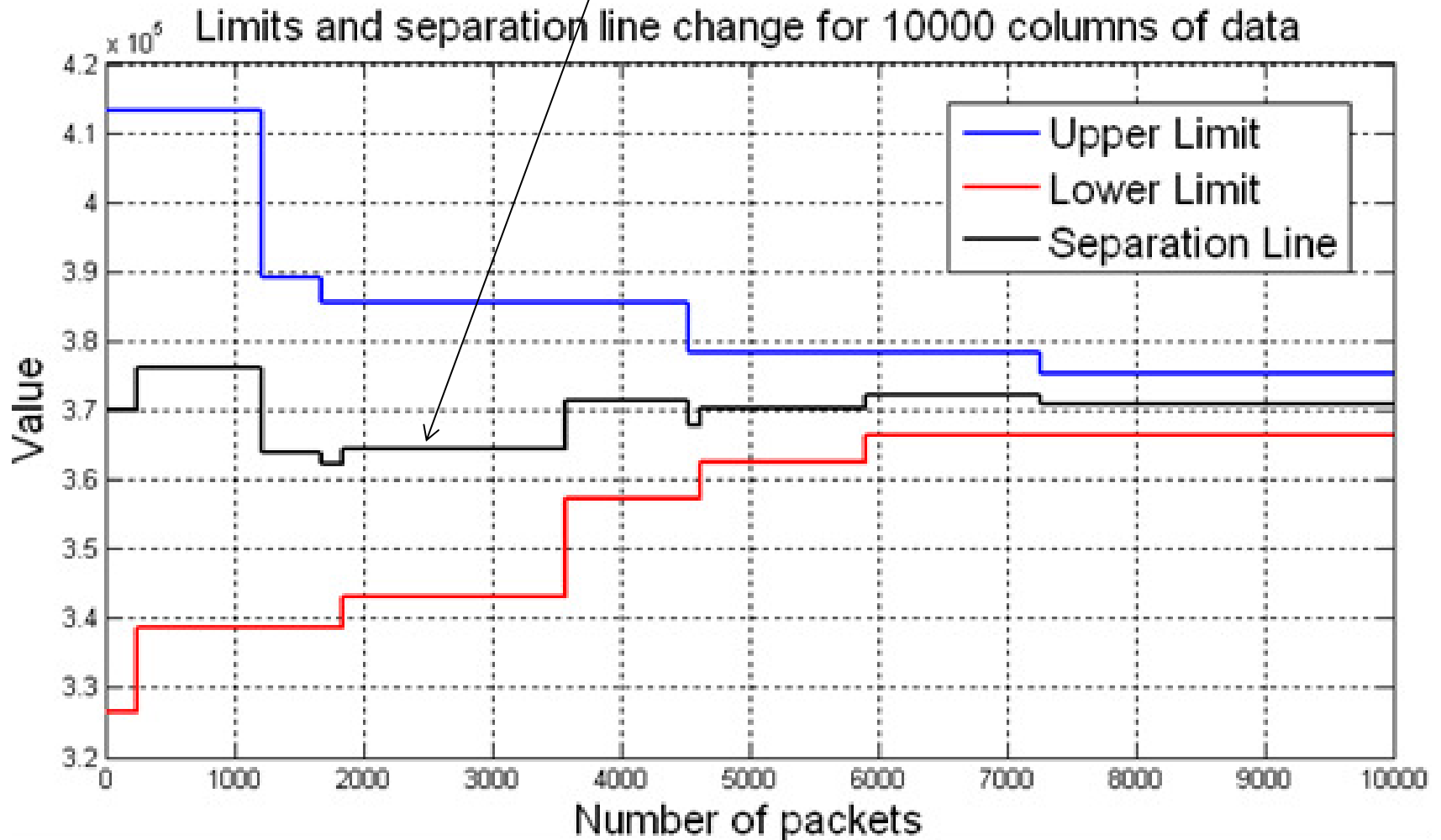


before decryption



after decryption =>  
Clear separation between  
corrupted and useful  
packets

## Adaptive threshold to separate corrupted/injected packets from the original ones



# Computational Overhead

- Communications Hub (SM) encoding:
  - PHE:  $O(N^2)$
  - Multiplications & modulus operations:  $O(N^2 \log n)$
- CSP encoding:
  - Per packet  $O(N^2 \log n)$
  - Total:  $O(N^3 \log n)$
- DCC decoding:
  - $O(N^2 \log n)$

# Conclusions

- With smart meter rollouts being deployed worldwide, it is critical to ensure secure transmission of sensitive personal data that is subject to eavesdropping and malicious attacks.
- We propose a combined homomorphic encryption algorithm with network coding that provides security and privacy while maintaining RLNC allowing for a high chance of recovering packets at the sink.
- Open work:
  - Implementation of lightweight verification scheme to prevent pollution attacks propagating throughout the network
  - Assessing robustness to a large scale attacks
  - Practical implementation

# Acknowledgements



- All presented work is being addressed as part of two UK Research Council projects by our team, within multi-disciplinary and multi-institutional (academic + industrial) consortiums
  - REFIT: Personalised Retrofit Decision Support Tools for UK Homes using Smart Home Technology
  - APAtSCHE: Aging Population Attitudes to Sensor Controlled Home Energy

# University of **Strathclyde** Glasgow

